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Spatially explicit regional wind erosion and dust emission modeling: Incorporating large- and small-scale variability

G. S. Okin, Department of Environmental Sciences, University of Virginia, PO Box 400123 , Charlottesville, VA 22904-4123, (okin@geog.ucsb.edu)

D. A. Gillette, Air Resources Laboratory (MD-81), Applied Modeling Research Branch, Research Triangle Park, NC 27711, (gillette.dale@epamail.epa.gov)

Introduction

Despite the importance of desert dust in global and regional scales, it is often unclear in detail where it is produced and what role humans play in mediating its production. The dust observed over North Africa, for example, certainly originates in the Sahara and Sahel regions, but current technologies do not allow unique identification of the loci in these landscapes of the greatest dust emission. Thus, controversy remains about the extent to which land use contributes to the atmospheric mineral dust. Recent work by Prospero *et al.* (In Press) and Ginoux *et al.* (2001) suggests that the overwhelming majority of desert dust comes from closed basins in arid areas related to now-dry or ephemeral lakes. They argue further that humans do not significantly perturb the dust cycle, a conclusion supported by Guelle *et al.* (2000). This point of view contrasts sharply with that of Tegen and Fung (1995) who suggest that land use may in fact dramatically affect the amount of dust emitted in desert regions.

We have created a spatially explicit wind erosion and dust flux model (SWEMO) that allows estimation of wind erosion and dust flux across a landscape by incorporating spatial distributions of important parameters. This approach provides a powerful basis for trying to understand how vegetation and soil interact in the landscape to create the dust sources. This approach is therefore applicable in trying to understand the most important or persistent dust sources in an area. The goal of SWEMO is to integrate soil and vegetation parameters from field studies or remote sensing in a robust model of dust sources. By explicitly incorporating random variations in derived parameter (e.g. lateral cover, threshold shear velocity on vegetated surfaces) and mass flux estimation in a Monte Carlo framework, SWEMO can accommodate the inherently nonlinear nature of wind erosion and dust flux. The inclusion of random variation in SWEMO highlights the importance of small but intense deflation surfaces on landscape-scale wind erosion and dust flux estimates.

Model Description

Wind erosion depends on several parameters that vary as a function of soil and vegetation cover. By using maps of dominant vegetation type and soil texture, SWEMO is able to impose spatial variability by allowing the main parameters that determine wind erosion and dust flux (see Table 1) to vary according to the specific soil and vegetation found at any location. However, even if categorical maps of soil texture and vegetation type, with polygons labeled, for example, "sandy loam" and "creosote", are 100% accurate, they do not represent the full variability of the landscape: among other things, the size and spacing of plants varies even among areas with the same polygon labels. Therefore, a stochastic modeling approach is implemented in SWEMO, allowing parameters to vary within a specific range. As a result, SWEMO is able to model, statistically, small areas not well represented by local averages. A small hole in vegetation, such as a natural disturbance, a road, a dry river, or a dry lake, may account for the majority of dust emitted in an area, but be insignificant on the scale at which most maps are produced.

SWEMO uses maps of soil texture and vegetation, in addition to knowledge of vegetation cover and size parameters, to derive maps of threshold shear velocity for a vegetates surface (u_{*tv}) and z_o. For each cell in the model, a histogram of shear velocity is derived from a histogram of wind speed at one height using the value of z_o at that cell. A mass flux equation (Shao and Raupach, 1993) is then evaluated for each cell to derive an estimate of total horizontal flux, Q_{Tot}. A soil-texture based value of the ratio of vertical flux to horizontal flux is use to calculate vertical flux, F_a. The processing stream for

Table 1. Relations between wind erosion model parameters and vegetation/soil parameters

Model Parameter		Vegetation/Soil Parameter
Threshold shear velocity of soil	u_{*ts}	Soil grain size, crusting, disturbance
Displacement height	D	Plant height & density
Roughness height	z_o	Plant height & density
Basal/Frontal area ratio	σ	Plant height & radius
Drag Coefficient ratio	β	Approx. constant (~100)
Lateral Cover	λ	Plant height, radius, & number density
Fractional Cover	C	Found directly from images
Number Density	N	Fractional cover & plant radius

SWEMO is depicted in Figure 1.

Methods

In the present study, a site with all requisite data (soil maps, vegetation maps, wind data, and a wealth of ongoing ecological research) was chosen to test SWEMO. The Jornada Basin in south-central New Mexico is a part of the National Science Foundation's Long-Term Ecological Research (LTER) network, and as such provides a wealth of required and ancillary data. The Jornada del Muerto basin lies approximately 30 km northeast of Las Cruces, NM, in the Chihuahuan Desert ecosystem.

Portions of the Jornada Basin have been mapped by the US Soil Conservation Service (1980). Each polygon in this soil map is labeled with a soil texture of the dominant soil type in that polygon, which allows estimation of u_{*ts} and F_a/Q_{Tot}. The particle-limitation coefficient is assumed to be 1.0 for the entire study area. Values of u_{*ts} used in this study were derived from mean values provided by Gillette (1988). Values of F_a/Q_{Tot} were estimated using data from Gillette et al. (1997).

A vegetation map of portions of the Jornada Basin was made available to this study through the Jornada LTER project (digital data produced by R. Gibbens, R.

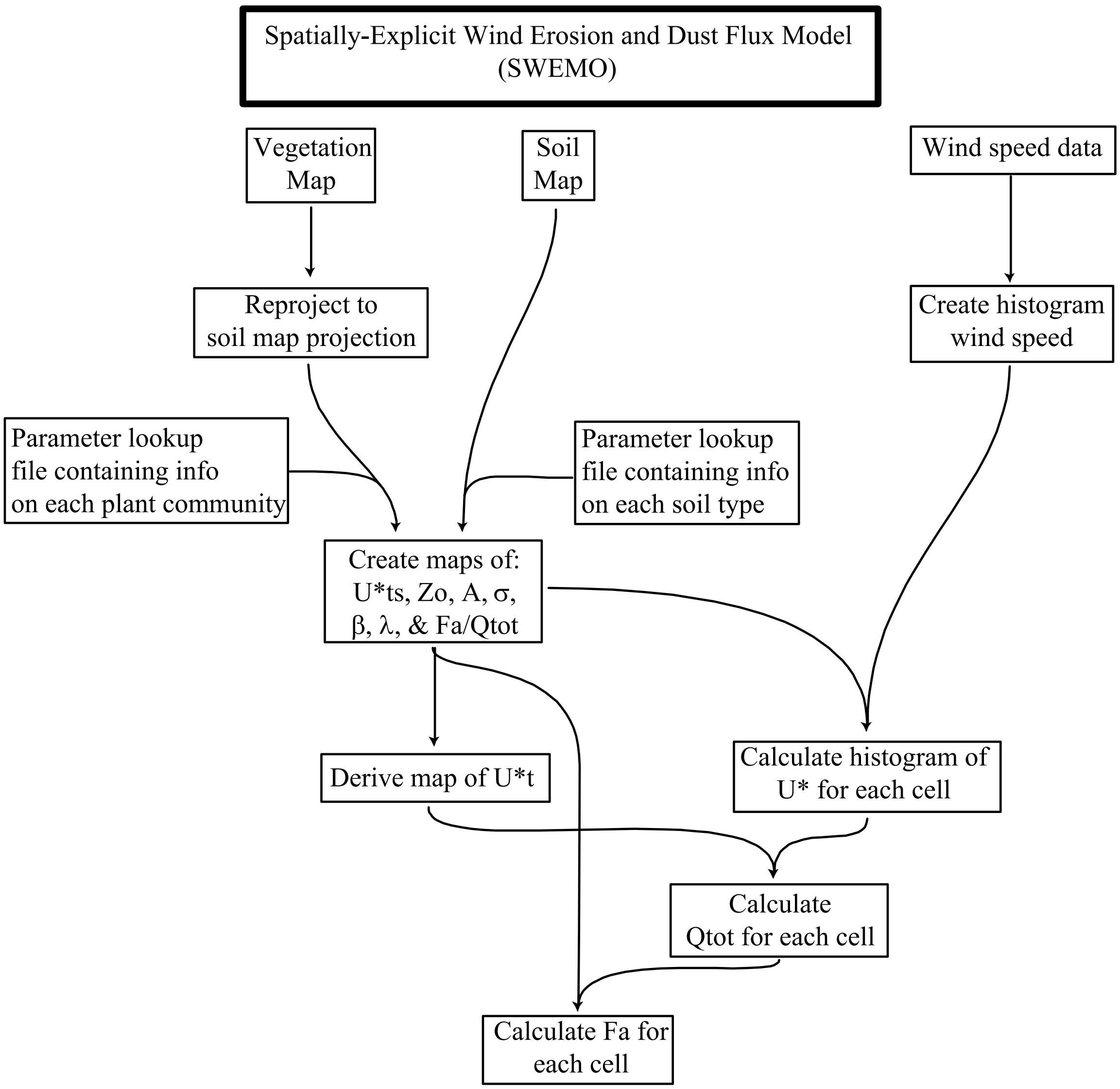

Figure 1. Processing stream for the spatially-explicit wind erosion and dust flux model (SWEMO)

McNeely, and B. Nolen). This map contained information on spatial distribution of the dominant plant communities in the basin: grassland, mesquite, creosote, tarbush, snakeweed, other shrubs, and no vegetation. Fractional cover for the grassland and snakeweed cover types and plant diameter and height for all vegetation cover types were derived from ongoing vegetation monitoring. Fractional cover for the creosote and tarbush cover types was derived from ongoing vegetation monitoring data as part of the Small Mammal Exclosure experiment at Jornada. Fractional cover for the creosote vegetation cover type was taken from Okin and Gillette (2001). Plants were assumed to be cylindrical in shape.

Wind monitoring by one of the present authors (D. Gillette) has been ongoing at several sites in the Jornada for many years. Data from one windy season (March 28, 2000 – July 10, 2000) was used in this study.

Results and Conclusion

By combining soil and vegetation maps with reasonable values for erosion-related soil and plant parameters, SWEMO has the potential of modeling wind erosion and dust flux on regional and landscape scales using relatively simple relations. The explicit incorporation of sub-grid variability through Monte Carlo simulation in the model allows more accurate estimation of derived-parameter and mass flux.

Because of the highly nonlinear nature of wind erosion and dust emission, they are highly sensitive to heterogeneity in the landscape. In particular, as heterogeneity increases, mass flux also increases for all surfaces. While increasing variability increases the incidence of both high and low erodibility surfaces, the high erodibility surfaces account for the bulk of the mass flux. Therefore, the modeling scheme used in SWEMO allows implicit modeling of erosion “hot spots” and more realistic estimation than modeling using mean surface parameters.

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